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The origin of magnetic fields in galaxies: Observational tests with the Square Kilometre Array

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The *all-sky survey of Faraday rotation*, a Key Science Project of the planned Square Kilometre Array, will accumulate tens of millions of rotation measure measurements toward background radio sources and will provide a unique database for characterizing the overall magnetic geometry of magnetic fields in galaxies and in the intergalactic medium. Deep imaging of the polarized synchrotron emission from a large number of nearby galaxies, combined with Faraday rotation data, will allow us to test *primordial, gas flow, and dynamo models* for field origin and amplification. The SKA will find the first magnetic fields in young galaxies and determine the timescale for building up small-scale turbulent and large-scale coherent fields. The spectrum of dynamo modes, if existing, will be resolved. The present-day coherent field may keep memory of the direction of the seed field which can be used for mapping the structure of the seed field before galaxy formation.

1 Introduction

Galactic magnetism may have evolved in subsequent stages:

(1) Field seeding by primordial fields embedded in the protogalaxy, or fields ejected into the protogalaxy by AGN jets, radio lobes, early supernova remnants, or gamma-ray bursts.
(2) Field amplification by compressing or shearing flows, turbulent flows, magneto-rotational instability, and dynamos.
(3) Field ordering by the large-scale dynamo.

Models referring to one or more of these stages can be tested by observations. Radio astronomy provides the best tools to measure galactic magnetic fields. The planned Square Kilometre Array (SKA) will allow fundamental advances in studying the origin and evolution of magnetic fields.

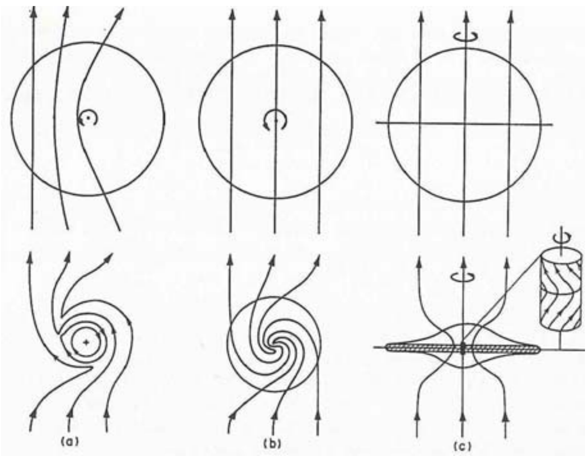

Fig. 1 Field structures (*bottom row*) generated from different large-scale protogalactic fields (*top row*) in a differentially rotating disk: (a) non-uniform field perpendicular to the rotation axis, (b) uniform perpendicular field, (c) uniform field parallel to the rotation axis (from Sofue 1990).

2 Models of magnetic field origin and evolution

2.1 "Primordial" models

A protogalactic seed field (not necessarily a primordial field from the early Universe) was amplified by compression during galaxy collapse and shearing by the differentially rotating galactic disk. To avoid winding up and field decay by reconnection, field diffusion through the disk gas has to be assumed (Fujimoto & Sawa 1987). If the seed field was random, the sheared field becomes *anisotropic random*. If the seed field had a large-scale direction, the structure of the resulting field depends on the angle between the seed field and the rotation axis of the disk (Sofue 1990). A seed field perpendicular to the rotation axis develops into a large-scale *bisymmetric* configuration in the disk (Fig. 1b), while a parallel seed field becomes *dipolar* (Fig. 1c). A non-uniform large-scale seed field may form an *axisymmetric* field in the central part of the disk (Fig. 1a).

A more realistic "primordial" model was developed by Howard & Kulsrud (1997) who introduced coupling of the field lines to gas clouds allowing for ambipolar diffusion. A seed field of any structure develops into an anisotropic ran-

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dom field with frequent reversals on a scale of about 100 pc, the *coherence length* of the field. Averaging the field over the galaxy generally yields a non-zero value, a weak large-scale field.

"Primordial" models are unrealistic because they neglect deviations from axisymmetric rotation of the gas, such as spiral density waves. Furthermore, such models suffer from a fundamental problem: Shear by differential rotation increases the average field strength, not the magnetic flux, while magnetic flux is lost into intergalactic space by magnetic diffusion. Estimation of turbulent diffusion leads to a decay time of the field of only 10^8 yr (Ruzmaikin et al. 1988). To maintain the field strength, field amplification by gas flows or a dynamo is required (Sect. 4.3).

2.2 "Flow" models

The present-day strength and structure of galactic magnetic fields may also be the result of *local* compression and shear by gas flows. In a kinematic approach Otmianowska-Mazur et al. (2002) showed that the gas flow in a barred galaxy (modelled in N-body simulations) can amplify fields and generate spiral structures with coherence lengths of a few 100 pc. Total magnetic energy and total magnetic flux decrease; a small-scale dynamo (Sect. 4.3) is required to maintain the field.

Dynamic MHD models of turbulent gas flows in galaxies driven by supernova explosions were computed only for limited volumes of about 1 kpc^3 (Korpi et al. 1999; de Avillez & Breitschwerdt 2005). The magnetic field is sheared and compressed by the flow and reveals a spectrum of coherent structures up to $\simeq$ 100 pc size. The strongest fields are located in the regions of cold, dense gas. This agrees well with the interpretation of the radio – infrared correlation (Sect. 3).

2.3 Dynamo models

The *mean-field α-Ω dynamo model* is based on differential rotation and the α-effect (Ruzmaikin et al. 1988; Beck et al. 1996). The physics of dynamo action still faces theoretical problems (Kulsrud 1999; Brandenburg & Subramanian 2005). The dynamo is the only known model which is able to generate large-scale *coherent* magnetic fields of spiral shape. These coherent fields can be represented as a superposition (spectrum) of modes with different azimuthal and vertical symmetries. In a smooth, axisymmetric gas disk the strongest mode is that with the azimuthal mode number $m = 0$ (*axisymmetric* spiral field), followed by the weaker $m = 1$ (*bisymmetric* spiral field), etc (Elstner et al. 1992). These modes cause typical variations of Faraday rotation along the azimuthal direction in a galaxy (Krause 1990). In flat, uniform disks the axisymmetric mode with *even* vertical symmetry (quadrupole) is excited most easily (Baryshnikova et al. 1987) while in spherical objects the *odd* symmetry (dipole) dominates. The timescale for building up a coherent field from a turbulent one is $\approx 10^9$ yr (Beck et al. 1994).

Real galaxies are not uniform. Consequently, recent dynamo models include the non-axisymmetric gas distribution in spiral arms (Moss 1998) or the gas flow in a bar potential (Moss et al. 2001), hence combining dynamo and flow models. Higher modes may be amplified faster than in the standard model. Gravitational interaction with another galaxy may also modify the mode spectrum and enhance the bisymmetric mode (Moss 1995).

3 Testing the models – present status

Total synchrotron intensity is a measure of total field strength and density of cosmic-ray electrons (and positrons). Assuming equipartition between the energy densities of magnetic field and cosmic rays, this energy density is similar to that of the kinetic energy of turbulent gas motions in galaxies (Beck 2005), as imposed by dynamo models. Synchrotron intensity is closely correlated with the infrared intensity. This striking fact tells us that cosmic-ray acceleration *and* field amplification are continuous processes and related to star formation, e.g. by field coupling to the ionized envelopes of cold gas clouds (Niklas & Beck 1997). However, the correlation is violated for very young starburst galaxies (Roussel et al. 2003). This could be due to the time needed for the evolution of massive stars to supernova remnants, which are believed to be the main cosmic-ray accelerators, but could also be the result of the finite timescale for dynamo amplification.

Most galaxies reveal spiral patterns in their polarization vectors, even flocculent or irregular galaxies. The radially decreasing pitch angles of the observed spiral patterns agree with the predictions of dynamo models (Beck 1993; Shukurov 2000). The spiral field can be coherent or incoherent (anisotropic). Faraday rotation measures (RM) are a signature of *coherent regular fields*. Large-scale RM patterns observed in several galaxies (Krause 1990; Beck 2005) show that some fraction of the magnetic field in galaxies has a large-scale coherent direction. The classical case is the strongly dominating axisymmetric field in the Andromeda galaxy M 31 (Berkhuijsen et al. 2003; Fletcher et al. 2004). A few more cases of dominating axisymmetric fields are known (e.g. the LMC, Gaensler et al. 2005), while dominating bisymmetric fields are rare (Krause et al. 1989). The two magnetic arms in NGC 6946 (Beck & Hoernes 1996), with the field directed towards the galaxy's centre in both, are a signature of superposed $m = 0$ and $m = 2$ modes. However, for most of the (about 20) nearby galaxies for which multi-frequency observations are available, angular resolutions and/or signal-to-noise ratios are still insufficient to reveal a mixture of magnetic modes – if existing.

Polarization angles are ambiguous by $\pm 180°$ and hence insensitive to field reversals. Compression or stretching of turbulent fields with random orientations generates incoherent *anisotropic random* fields which reverse their direction

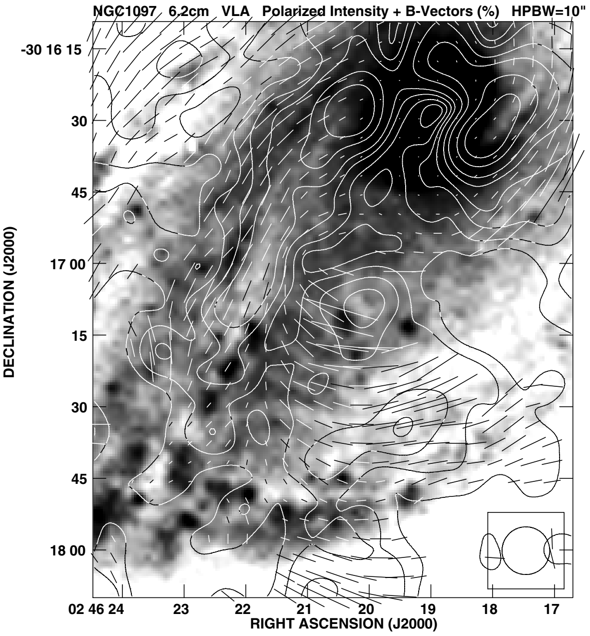

Fig. 2 Polarized intensity contours and observed B-vectors ($E+90°$) of the central and southern parts of NGC 1097 at $\lambda\,6.2$ cm at $10''$ resolution. The background optical image was kindly provided by Halton Arp (from Beck et al. 2005).

frequently within the telescope beam, so that Faraday rotation of the extended polarized emission is small while the degree of polarization can still be high. Observations of several spiral galaxies revealed a highly ordered spiral pattern in the polarization (B-) vectors, but small Faraday rotation, so that anisotropic random fields seem to dominate over the coherent regular ones. Such fields are predicted by flow models (Sect. 2.2). A striking example is the barred galaxy NGC 1097 where the high degree of polarization along the southern bar is mostly due to compressed random fields (Fig. 2). Ram pressure from the intracluster gas or interaction between galaxies have a similar compressional effect (Chyży et al., this volume; Chyży & Beck 2004). Dwarf irregular galaxies with almost chaotic rotation host turbulent fields with strengths comparable to spiral galaxies, but no large-scale coherent fields (Chyży et al. 2003).

The structure of coherent (regular) fields may extend to small scales which cannot be resolved by present-day observations, e.g. elongated field loops in the disk or Parker loops. Observations at higher resolution are needed to distinguish between anisotropic random and unresolved regular fields.

Present-day observations are limited by sensitivity at high resolution. Polarized intensities are low and can be detected only with large single-dish telescopes (Effelsberg, GBT) and with the VLA and ATCA in compact configurations. Hence, the best available spatial resolutions for polarization and Faraday rotation studies are only 300–500 pc in the nearest spiral galaxies. Galaxies beyond $\simeq$ 20 Mpc distance cannot be sufficiently resolved in polarization.

The rotation measures toward polarized, point-like background sources do not suffer from limited resolution. Such data are scarce due to limited sensitivity. As their number increases with the angular size of the galaxy, only the largest ones were studied so far. Han et al. (1998) found 21 polarized sources behind M 31, Gaensler et al. (2005) about 100 sources behind the LMC.

4 Testing the models with the SKA

The *all-sky survey of Faraday rotation*, a SKA Key Science Project, will accumulate tens of millions of rotation measure (RM) measurements toward background radio sources (Gaensler et al. 2004). This will provide a unique database for understanding the structure and evolution of magnetic fields in galaxies and in the intergalactic medium (Beck & Gaensler 2004). *Faraday tomography* of the Milky Way at $\leq$ 1 GHz will yield a high-resolution three-dimensional picture of the magnetic field within a few kpc of the Sun. High-resolution synchrotron imaging at ≥ 5 GHz of a large number of nearby galaxies, combined with Faraday rotation data, will allow us to determine their magnetic field structure, and to test both the dynamo and primordial field theories for field origin and amplification.

Typical polarization intensities of nearby galaxies at 5 GHz are $\sim$0.1 mJy per $15''$ beam. Within a $1''$ beam, ~ 0.4 μJy is expected which the SKA can detect in ~ 1 hour of integration. This will allow polarization and Faraday rotation mapping in galaxies out to a distance of about 100 Mpc. Furthermore, such observations will reveal a large number of RM values toward background sources which can be used for an independent investigation of the detailed field structure.

4.1 Primordial against dynamo models

A large sample of data on the total and polarized synchrotron intensity and Faraday rotation in young galaxies will clarify the timescales for the generation of large-scale coherent and of small-scale fields, to be compared with the models. The SKA will also provide RM data toward sources behind galaxies with little or no star formation, like dwarfs and ellipticals, where no synchrotron emission is detectable but magnetic fields may exist, triggered by turbulence driven by type I supernovae (Moss & Shukurov 1996).

The SKA will confidently determine the Fourier spectrum of dynamo modes. The azimuthal mode of order m has $2m$ reversals and can be detected if $\simeq 10(m+1)$ independent azimuthal sectors are resolved in the disk of the galaxy. Let Θ be the telescope's angular resolution, R the mean radius of polarized emission, i the disk's inclination ($i = 0$ for face-on) and D its distance. The highest resolvable mode is $m_{\max} \approx \pi R \cos i / 5\Theta D - 1$. To resolve all modes up to $m = 4$ in a galaxy of 5 kpc radius and 45^o inclination at a distance of 100 Mpc, a resolution of $\approx 1''$ at a few GHz is required which the SKA will easily provide with high signal-to-noise ratio. As the average RM signal from a coherent field parallel to the disk plane varies with $\sin i$, mildly inclined galaxies are preferable.

The SKA has the potential to increase the galaxy sample with well-known field patterns by up to three orders of magnitude. The conditions for the excitation of dynamo modes can be clarified. For example, interactions with companion galaxies may enhance the bisymmetric $m = 1$ mode (Sect. 2.3). A dominance of bisymmetric fields for non-interacting galaxies would be in conflict with existing dynamo models and would support the primordial field origin (Sect. 2.1).

Galactic dynamo models also predict the preferred generation of quadrupolar patterns (Sect. 2.3) where the field in the disk has the same sign above and below the plane. Primordial models predict dipolar patterns with a reversal in the plane (Fig. 1c) which can be distinguished by observing RM in edge-on galaxies. However, their polarized emission is weak in the disk (due to strong depolarization) and also in the halo (strong energy losses of the cosmic-ray electrons). The determination of the global vertical field symmetry has not been possible yet. This experiment also must await the SKA.

The rotation measure toward background sources will allow us to trace coherent fields to large galactic radii and hence to derive restrictions for dynamo action. If the α effect is driven by supernova remnants or by Parker loops (Hanasz, this volume), dynamo modes should be excited preferably in the star-forming regions. If the magneto-rotational instability is the source of turbulence and of the α effect (Sellwood & Balbus 1999; Kitchatinov & Rüdiger 2004), field amplification will be seen out to large galactic radii.

4.2 Large-scale seed fields

Most of the (few) galaxies known to host a dominating axisymmetric $m = 0$ mode possess a radial field component, directed *inwards* everywhere (Krause & Beck 1998). The field direction in dynamo models preserves the memory of the direction of the large-scale seed field. The sign of the radial field component follows from the observed Faraday rotation (RM) and rotational velocity along the line of sight (v_r) on the major axis (Fig. 3): opposite signs of RM and v_r indicate an inward-directed field, same signs an outward-directed field. SKA's sensitivity and broad frequency bands will allow to observe a large sample to more than 100 Mpc distance and to map the structure of the large-scale seed field before galaxy formation.

4.3 Gas flow and small-scale dynamo

The failure to detect a coherent magnetic field in a resolved galaxy would indicate that mean-field dynamo action (Sect. 2.3) is unimportant (e.g. due to its long timescale) and that gas flows structure the field, supported by the *small-scale* or *fluctuation dynamo* (Subramanian 1998; Brandenburg & Subramanian 2005, see also this volume). It amplifies turbulent, incoherent magnetic fields, does not rely on differential rotation, and can work in all galaxy types. The detection of predominantly turbulent fields with the SKA would favour such models.

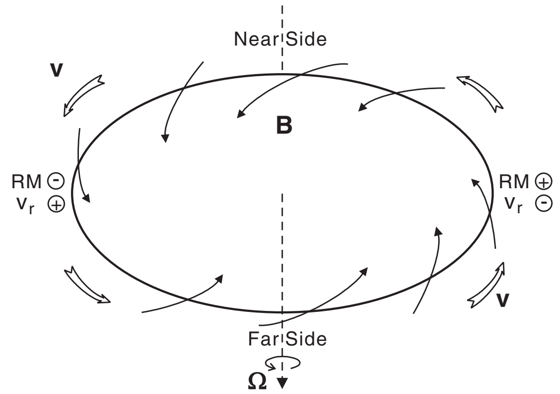

Fig. 3 Inward-directed axisymmetric magnetic field in an inclined galaxy with trailing spiral arms. The signs of Faraday rotation measure RM and rotational velocity v_r along the line of sight are indicated at the major axis (from Krause & Beck 1998).

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